

*N*-slit interferometer for secure free-space optical communications: 527 m intra interferometric path length

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2011 J. Opt. 13 035710

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1. REPORT DATE <b>2011</b>	2. REPORT TYPE		3. DATES COVERED <b>00-00-2011 to 00-00-2011</b>		
4. TITLE AND SUBTITLE <b>N-Slit interferometer for secure free-space optical communications: 527 m intra interferometric path length</b>			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Interferometric Optics,, ,Rochester,NY,14626-0592</b>			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>This a US Army High Energy Laser Laboratory project funded through a subcontract to BAE Systems.</b>					
14. ABSTRACT <b>The N-slit interferometer is demonstrated to function with an intra interferometric propagation path length of 527.33 m. Interferograms representing several interferometric characters, corresponding to N = 2, 3, 4, and 5, were recorded at the interferometric plane located at the end of an open air propagation range. Interferometric computations, based on the application of Dirac's notation, were successfully used to predict the structure and divergence of the propagating interferograms. These measurements were carried out during an unusual mild-temperature, low-humidity, summer night in northern Alabama. In the laboratory, at an intra interferometric propagation path length of 7.235 m, the N-slit interferometer was also used to successfully detect the intrusion of microscopic fibers into the intra interferometric propagation path. These experiments led to the detection of diffraction patterns superimposed over the interferograms.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Public Release</b>	18. NUMBER OF PAGES <b>6</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

# $N$ -slit interferometer for secure free-space optical communications: 527 m intra interferometric path length

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Received 5 November 2010, accepted for publication 30 December 2010

Published 3 February 2011

Online at [stacks.iop.org/JOpt/13/035710](http://stacks.iop.org/JOpt/13/035710)

## Abstract

The  $N$ -slit interferometer is demonstrated to function with an intra interferometric propagation path length of 527.33 m. Interferograms representing several interferometric characters, corresponding to  $N = 2, 3, 4$ , and  $5$ , were recorded at the interferometric plane located at the end of an open air propagation range. Interferometric computations, based on the application of Dirac's notation, were successfully used to predict the structure and divergence of the propagating interferograms. These measurements were carried out during an unusual mild-temperature, low-humidity, summer night in northern Alabama. In the laboratory, at an intra interferometric propagation path length of 7.235 m, the  $N$ -slit interferometer was also used to successfully detect the intrusion of microscopic fibers into the intra interferometric propagation path. These experiments led to the detection of diffraction patterns superimposed over the interferograms.

**Keywords:** aviation, beam expansion, clear air turbulence, Dirac notation, free-space, propagation, interferometric character, interferometric imaging,  $N$ -slit interference,  $N$ -slit interferometer,  $N$ -slit interferometry, natural fibers

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Recently, we reported on an  $N$ -slit interferometer with an intra interferometric path length of 35 m [1]. In the present experiments we have extended the intra interferometric propagation distance to 527.33 m. The experiment was carried out, at night, using the full available length of an existing open air propagation range. These experiments were performed using several theoretically predicted interferometric characters corresponding to  $a, b, c, d$  ( $N = 2, 3, 4, 5$ , respectively) [2] under night-time atmospheric conditions. The successful completion of these open air propagation experiments

represent a significant development on this free-space optics communications technique, originally demonstrated in the laboratory over a propagation distance of only 10 cm and envisioned primarily as a space-to-space secure interferometric communications technique [2].

Previously, the integrity of this free-space interferometric communications technique has been demonstrated via the *catastrophic collapse* of the interferometric characters, or signal, resulting from attempts to insert thin beam splitters into the propagation path [1–3]. A refinement in the interception technique consists in the subtle insertion of microscopic fibers into exact positions in the intra interferometric

path. Experiments performed in the laboratory, at an intra interferometric distance of  $D_{\langle x|j \rangle} = 7.235$  m, demonstrate that the interferograms easily detect the presence of very thin natural fibers, thus upholding the integrity of this interferometric approach for free-space communications. The detection of the fibers occurs via the superimposition of distinct diffraction patterns over the interferometric characters.

So far,  $N$ -slit interferometers have been used in various industrial metrology tasks including microdensitometry, microscopy, and optical modulation measurements of thin film gratings generated from a variety of manufacturing processes [4]. The present experiments demonstrate that  $N$ -slit interferometers are also applicable to secure terrestrial free-space optical communications over propagation distances of practical interest. Additional applications include the detection of even mild clear air turbulence [1] over various distances of practical interest without fundamental limitations on its propagation range.

## 2. Theory

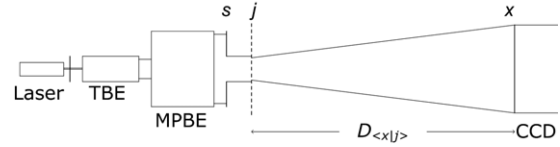
As mentioned in [1], light propagation through  $N$ -slit arrays was studied by Newton [5] and  $N$ -slit diffraction was discussed by Michelson [6]. In a more contemporaneous setting, Feynman [7] applied Dirac's quantum notation [8] to perform double-slit thought experiments on electrons. This approach was applied to the  $N$ -slit interferometer (see figure 1), for narrow-linewidth laser illumination, thus yielding the generalized, one-dimensional,  $N$ -slit interference equation [9, 10]

$$|\langle x|s \rangle|^2 = \sum_{j=1}^N \Psi(r_j) \sum_{m=1}^N \Psi(r_m) e^{i(\Omega_m - \Omega_j)} \quad (1a)$$

or

$$|\langle x|s \rangle|^2 = \sum_{j=1}^N \Psi(r_j)^2 + 2 \sum_{j=1}^N \Psi(r_j) \times \left( \sum_{m=j+1}^N \Psi(r_m) \cos(\Omega_m - \Omega_j) \right). \quad (1b)$$

In either equation,  $s$  represents the photon source,  $j$  refers to the  $j$ th slit in the transmission grating,  $x$  represents the interference plane,  $\Psi(r_j)$  are wavefunction amplitudes of 'ordinary wave optics' [8, 11], and the term in parenthesis represents the phase which describes the exact geometry of the  $N$ -slit interferometer [10, 11]. As discussed in [1], this equation was originally derived for single-photon propagation, albeit in practice it also applies to an ensemble of indistinguishable photons [12], as in the case of narrow-linewidth laser emission. This approach [10, 12] is consistent with van Kampen's quantum theorems [13]. The nexus between the probability distribution  $|\langle x|s \rangle|^2$  and measured interferometric profiles is also described in [12]. As previously emphasized, an important advantage of this quantum interference equation is the continuous description of measured interferograms from the near- to the far-field [10].



**Figure 1.** Top view schematics of the  $N$ -slit interferometer as described in [1].  $N$  slits are illuminated at a transmission grating ( $j$ ) thus allowing the propagation of an  $N$ -slit interference signal, along  $D_{\langle x|j \rangle}$ , toward the interferometric plane  $x$ , at which is located a CCD detector array. For  $D_{\langle x|j \rangle} = 527.33$  m, the CCD detector is replaced by a flat surface deployed at  $x$ . TBE is a telescopic beam expander providing an expansion factor of  $M \approx 10$ . The MPBE is a one-dimensional multiple-prism beam expander with  $M \approx 5$  (from [1]).

## 3. Experiments

Experimental details describing the  $N$ -slit interferometer, shown in figure 1, are given in [1]. It is however necessary to mention that the illumination source is a single-transverse-mode narrow-linewidth He–Ne laser ( $\lambda = 632.8$  nm) and the two gratings used were: one grating with  $570 \mu\text{m}$  slits separated by  $570 \mu\text{m}$  isles and a grating with  $1000 \mu\text{m}$  slits separated by  $1000 \mu\text{m}$  isles. The tolerances in the slit dimensions are quoted by the manufacturer as  $0.5 \mu\text{m}$ , with further details given in [1].

The  $570 \mu\text{m}$  grating was employed in the experiments designed for the detection of thin natural fibers at  $D_{\langle x|j \rangle} = 7.235$  m, while the  $1000 \mu\text{m}$  grating was used to obtain the results with the  $D_{\langle x|j \rangle} = 527.33$  m configuration.

As discussed in [2], for both gratings a series of interferometric characters were created by illuminating an increasing number of slits. That is,  $a$ ,  $b$ ,  $c$ , and  $d$ , interferometric characters were generated by the corresponding illumination of  $N = 2, 3, 4$ , and  $5$  slits respectively.

As in the previous indoor experiment (at  $T \approx 22^\circ\text{C}$ ) the detector for the  $D_{\langle x|j \rangle} = 7.235$  m measurements is a Princeton Instrument (Pixis 100) CCD array composed of 1340 pixels each  $\sim 20 \mu\text{m}$  in width. This CCD array is deployed at the interferometric plane ( $x$ ). Two types of natural fibers were used: initially, fine human hair with a diameter of  $\sim 50 \mu\text{m}$ , and subsequently, a spider web fiber with a diameter in the  $25\text{--}30 \mu\text{m}$  range.

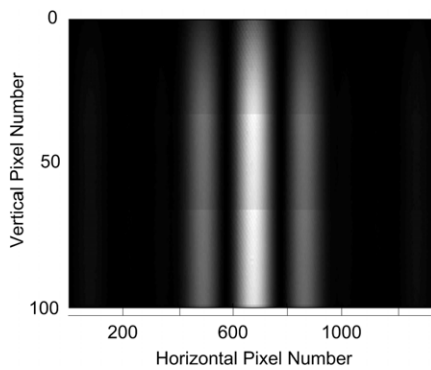
For the experiment on the extended configuration, at  $D_{\langle x|j \rangle} = 527.33$  m, the interferometric plane ( $x$ ) was comprised of a calibrated screen and the interferograms were recorded using digital photography. The illumination-grating part of the interferometer was mounted on a small optical table [1] and deployed at an elevation of  $15.17$  m, whilst the interferometric plane was deployed on a small hill at an intra interferometric distance of  $D_{\langle x|j \rangle} = 527.33$  m, as measured with a calibrated laser range finder. These experiments were performed during a clear summer night with atmospheric conditions characterized by an ambient temperature of  $T \approx 24^\circ\text{C}$  and a humidity of  $\sim 66\%$ .



**Figure 2.** Interferogram registered at  $x$ , for  $D_{(x|j)} = 527.33$  m,  $\lambda = 632.8$  nm, and  $N = 4$  (1000  $\mu\text{m}$  slits separated by 1000  $\mu\text{m}$ ), recorded in open air at  $T \approx 24^\circ\text{C}$  and a humidity of 66%. This interferogram corresponds to the interferometric character  $c$ . The horizontal scale at the base of the figure is 5 cm/div (whilst the less visible upper scale is 1 cm/div).



**Figure 3.** Interferogram registered at  $x$ , for  $D_{(x|j)} = 527.33$  m,  $\lambda = 632.8$  nm, and  $N = 5$  (1000  $\mu\text{m}$  slits separated by 1000  $\mu\text{m}$ ), recorded in open air at  $T \approx 24^\circ\text{C}$  and a humidity of 66%. This interferogram corresponds to the interferometric character  $d$ . The horizontal scale at the base of the figure is 5 cm/div (whilst the less visible upper scale is 1 cm/div).



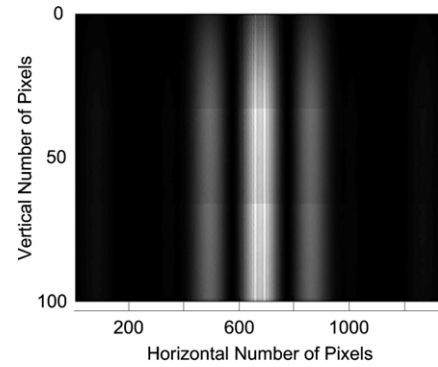
**Figure 4.** Control interferogram registered at  $x$ , for  $D_{(x|j)} = 7.235$  m,  $\lambda = 632.8$  nm, and  $N = 2$  (570  $\mu\text{m}$  slits separated by 570  $\mu\text{m}$ ) at  $T \approx 22^\circ\text{C}$ . This interferogram corresponds to the interferometric character  $a$ .

#### 4. Results

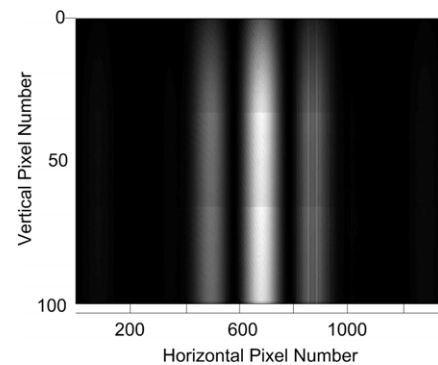
A measured interferogram, resulting from the illumination of  $N = 4$  slits of the 1000  $\mu\text{m}$  grating, at  $D_{(x|j)} = 527.33$  m, through the open atmosphere at  $T \approx 24^\circ\text{C}$  and a humidity of 66%, is shown in figure 2. The corresponding measurement under nearly identical propagation conditions, for  $N = 5$ , is shown in figure 3.

A measured interferogram, resulting from the illumination of  $N = 2$  slits of the 570  $\mu\text{m}$  grating, at  $D_{(x|j)} = 7.235$  m, in the laboratory and in the absence of turbulence at  $T \approx 22^\circ\text{C}$ , is shown in figure 4. The corresponding measurement under identical propagation conditions, for  $N = 2$ , with a spider web fiber deployed orthogonally to the propagation plane (that is, parallel to the grooves of the grating) is shown in figure 5.

The fiber is positioned 15 cm from the detection plane ( $x$ ) and intersects the main interference order, as demonstrated



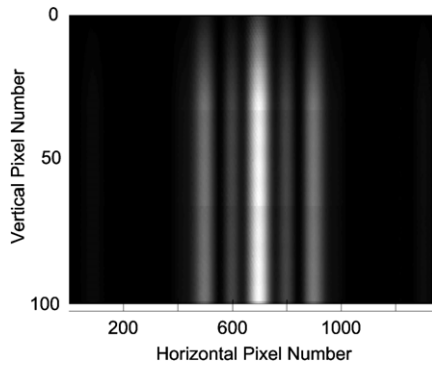
**Figure 5.** Interferogram registered at  $x$ , for  $D_{(x|j)} = 7.235$  m,  $\lambda = 632.8$  nm, and  $N = 2$  (570  $\mu\text{m}$  slits separated by 570  $\mu\text{m}$ ) with a spider web fiber deployed orthogonally to the propagation plane (that is, parallel to the slits, or perpendicular to the plane of figure 1) at a distance of 15 cm from  $x$ . The diffraction pattern, generated by the fiber, is superimposed over the central order of the interferogram.



**Figure 6.** Interferogram registered at  $x$ , for  $D_{(x|j)} = 7.235$  m,  $\lambda = 632.8$  nm, and  $N = 2$  (570  $\mu\text{m}$  slits separated by 570  $\mu\text{m}$ ) with a spider web fiber deployed orthogonally to the propagation plane (that is, parallel to the slits, or perpendicular to the plane of figure 1) at a distance of 15 cm from  $x$ . The diffraction pattern, generated by the fiber, is superimposed over the *outer right wing* of the interferogram.

by the diffraction pattern superimposed over the central order of the interferogram in figure 5. For comparison purposes the fiber is displaced to intersect the *outer right wing* of the interferogram, as demonstrated by the diffraction pattern superimposed over the right secondary maximum of the interferogram in figure 6.

A measured interferogram, resulting from the illumination of  $N = 3$  slits of the 570  $\mu\text{m}$  grating, at  $D_{(x|j)} = 7.235$  m, in the laboratory and in the absence of turbulence at  $T \approx 22^\circ\text{C}$  is shown in figure 7. The corresponding measurement under identical propagation conditions, for  $N = 3$ , with a spider web fiber deployed orthogonally to the propagation plane (that is, parallel to the grooves of the grating) is shown in figure 8. The fiber is positioned 15 cm from the detection plane ( $x$ ) and intersects the outer right wing of the interferogram, as demonstrated by the diffraction pattern superimposed over the outer right wing of the interferogram in figure 8.



**Figure 7.** Control interferogram registered at  $x$ , for  $D_{(x|j)} = 7.235$  m,  $\lambda = 632.8$  nm, and  $N = 3$  ( $570 \mu\text{m}$  slits separated by  $570 \mu\text{m}$ ) at  $T \approx 22^\circ\text{C}$ . This interferogram corresponds to the interferometric character  $b$ .

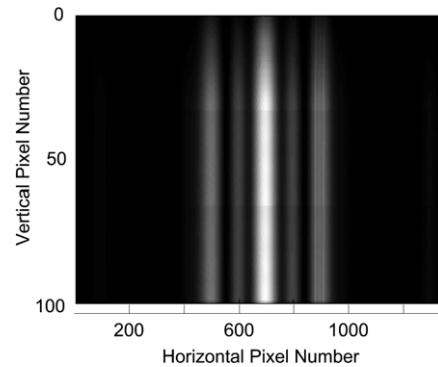
## 5. Discussion

The atmospheric propagation experiments using an intra interferometric path length of  $D_{(x|j)} = 527.33$  m consisted in propagating the interferometric characters  $a$ ,  $b$ ,  $c$ ,  $d$ , corresponding to  $N = 2, 3, 4, 5$ , using the  $1000 \mu\text{m}$  grating. The recorded interferograms, for  $c$  and  $d$ , are shown in figures 2 and 3. Planning for these experiments was facilitated by the accurate prediction of the interferograms via the interferometric equation. Predicted and recorded interferograms, in regard to the overall divergence of the interferometric patterns and the position of the spatial features of the interferograms, agree within 1–2%. Improved accuracy should be available by replacing the interference plane screen with tiled CCD detectors, which for this class of intra interferometric distance should provide a 40–50 cm detection width.

Digital movie recordings of the interferograms reveal mainly slight variations in the intensity domain of the interferograms, which are consistent with incipient atmospheric turbulence conditions [1, 4], most likely due to a mild breeze present during the experiments, even though the temperature ( $T \approx 24^\circ\text{C}$ ) and humidity ( $\sim 66\%$ ) were very favorable for unperturbed propagation. Previously [1], slight variations in the interferograms, for  $D_{(x|j)} = 35$  m, were detected even in an enclosed environment at  $T \approx 30^\circ\text{C}$ .

The results disclosed in this paper, with  $D_{(x|j)} = 527.33$  m, represent a significant advance in interferometric free-space optics communications, which were initially demonstrated in the laboratory over a propagation distance of only 10 cm and mainly envisioned as a space-to-space secure optics communications alternative [2]. Certainly, the propagation path demonstrated here opens the realm of application for free-space interferometric communications via the terrestrial atmosphere over propagation distances of practical interest. Further applications include the detection of even mild clear air turbulence [1] over various distances applicable to commercial aviation runways.

In previous publications [1–3] it has been indicated that the integrity of the interferometric characters is protected by the fundamental physics of interference [2, 7], which



**Figure 8.** Interferogram registered at  $x$ , for  $D_{(x|j)} = 7.235$  m,  $\lambda = 632.8$  nm, and  $N = 3$  ( $570 \mu\text{m}$  slits separated by  $570 \mu\text{m}$ ) with a spider web fiber deployed orthogonally to the propagation plane (that is, parallel to the slits, or perpendicular to the plane of figure 1) at a distance of 15 cm from  $x$ . The diffraction pattern, generated by the fiber, is superimposed over the *outer right wing* of the interferogram.

tells us that any attempt to observe the intra interferometric signal will distort or destroy the signal. Indeed, the use of ultrathin transparent beam splitters deployed near Brewster's angle, its least disruptive configuration, causes the collapse of the propagating interferometric characters [1–3]. In order to empirically investigate the effect of finer methods of intersection in these experiments we used spider web fibers. The experiments were conducted in the laboratory, at  $D_{(x|j)} = 7.235$  m, for  $N = 2, 3, 4, 5$ .

The results for  $N = 2$ , and 3 are shown in figures 5, 6, and 8. The beautiful diffraction patterns superimposed over the interferometric characters  $a$  and  $b$ , either at the central order or outlying positions, clearly demonstrate that free-space communications using  $N$ -slit interferometry can detect even very subtle methods of intrusion.

## 6. Conclusion

In this paper we report on the  $N$ -slit interferometer with the largest intra interferometric path length to date,  $D_{(x|j)} = 527.33$  m. Thus, we have proven that the  $N$ -slit interferometer is a viable interferometric tool over long free-space propagation paths under fair atmospheric conditions. It has also been demonstrated, in a laboratory environment, that even very subtle attempts to intercept the interferometric characters, using microscopic natural fibers, are readily detected via the observation of diffraction patterns superimposed over the interferometric signal. This is a new interferometric effect, which to our knowledge has not been previously reported.

These experimental observations, plus the data collected in previous experiments [1–3], lead us to conclude that  $N$ -slit interferometers with large intra interferometric path lengths are ready for the next stage of development into practical configurations, either for secure free-space communication systems or interferometric detection of clear air turbulence in airfields.

## Acknowledgment

This a US Army High Energy Laser Laboratory project funded through a subcontract to BAE Systems.

*Note added in proof.* The interferograms with superimposed diffraction patterns, as in figures 5, 6, and 8, can be theoretically described using the method disclosed in [10] that allows the characterization of interference via a series of  $N$ -slit arrays along the propagation axis [10].

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